New frontiers in computational cosmology: radiation hydrodynamics

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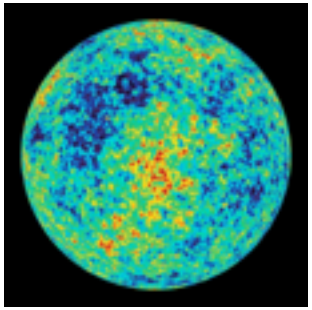
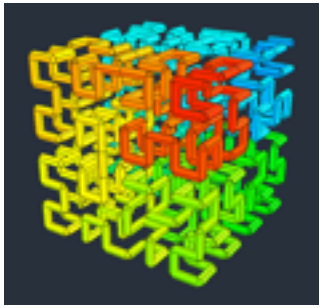
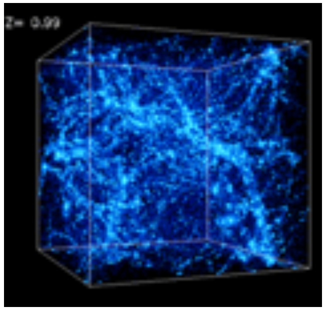
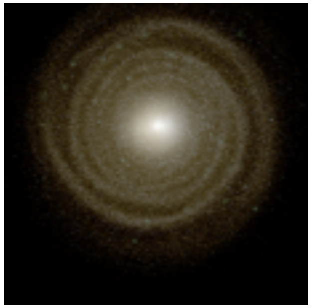
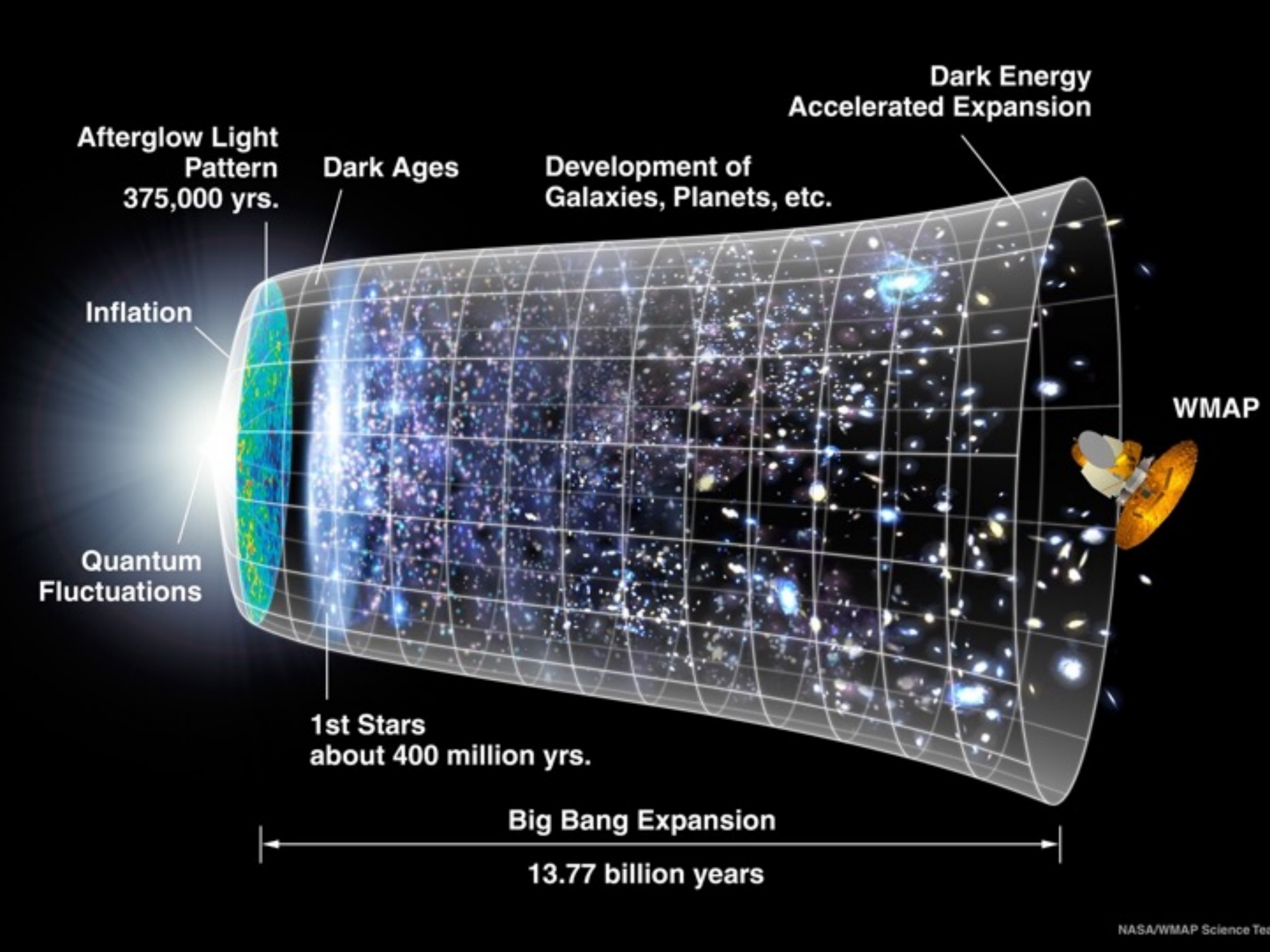
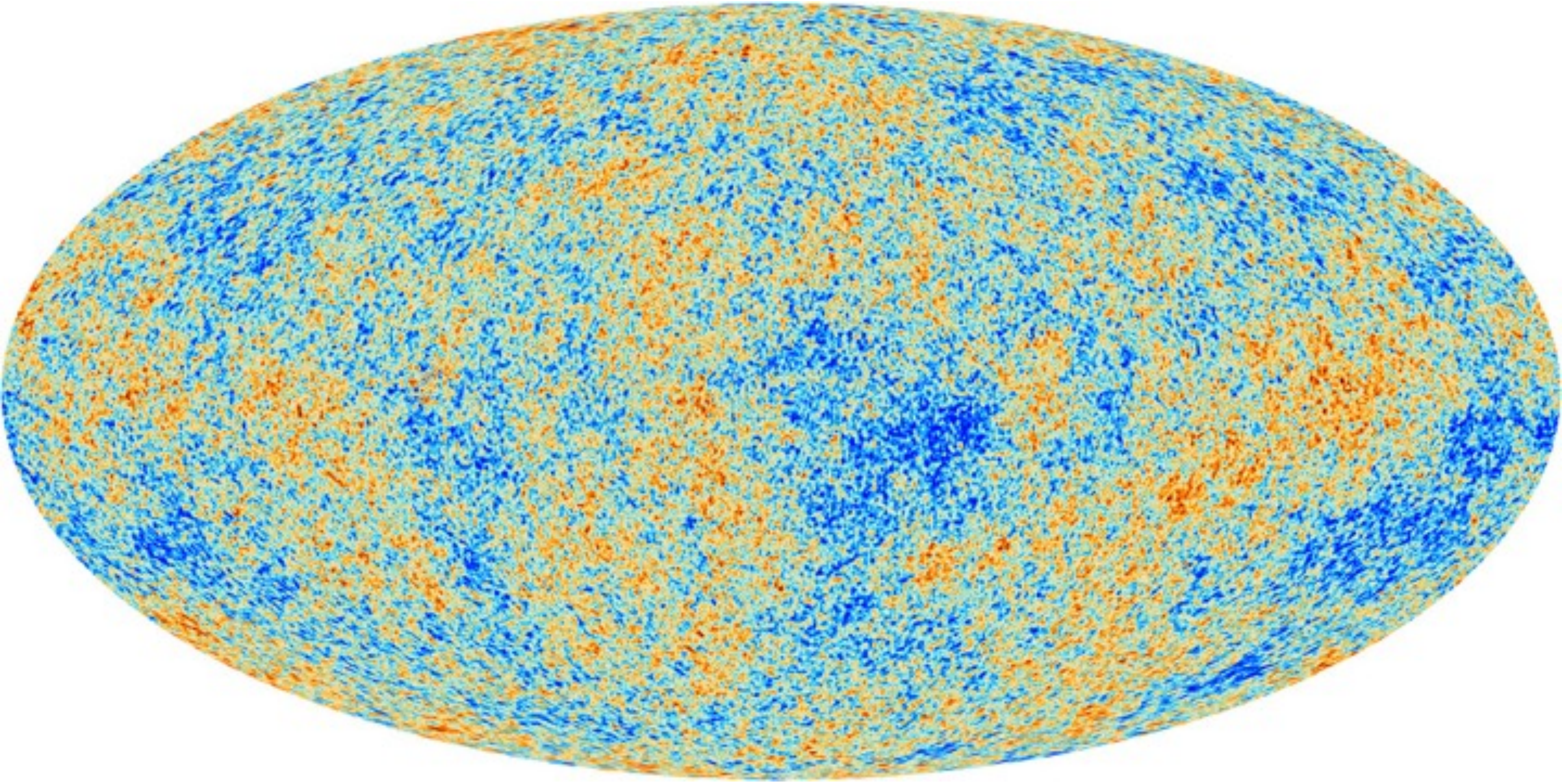





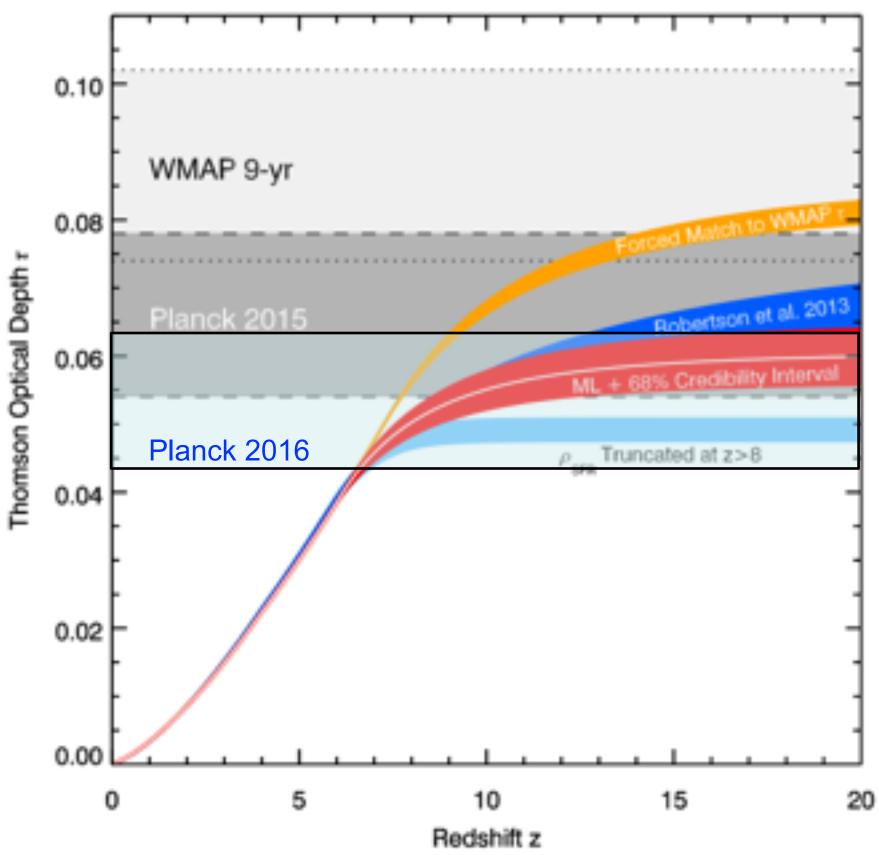

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years
NASA/WMAP Science

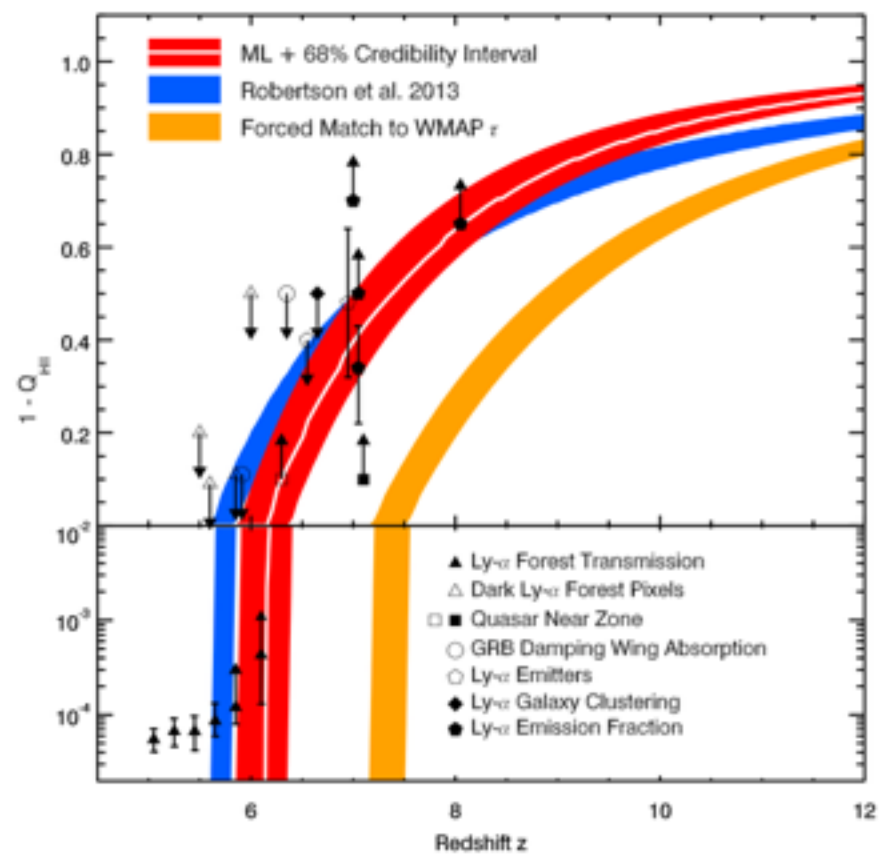
Planck satellite took a picture of the infant universe



Planck data release 5 Feb. 2015

Constraint on the reionization epoch





Robertson et al. (2015)

Constraint on the reionization epoch

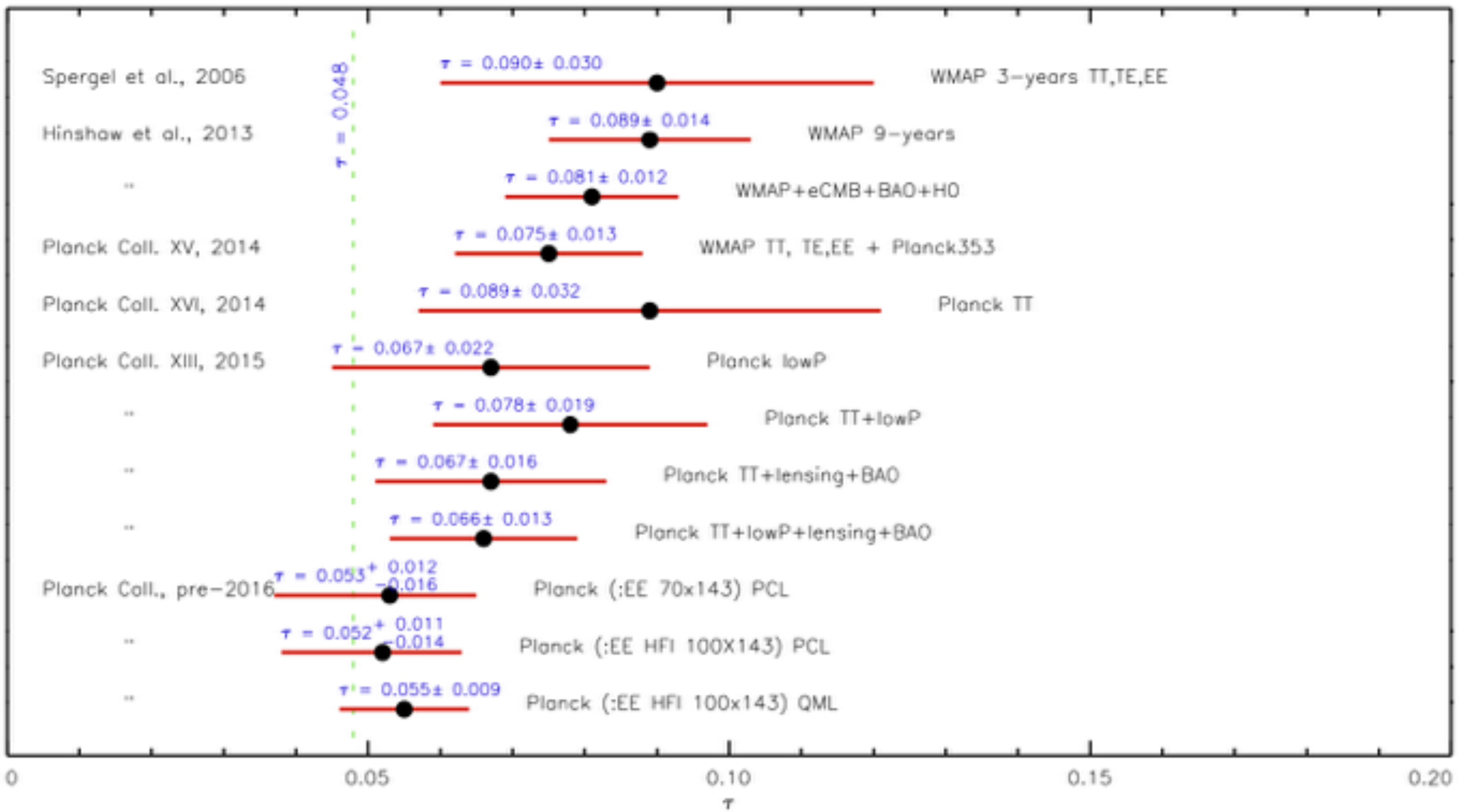


Fig. 41. History of τ determination with WMAP and *Planck*. We have omitted the first WMAP determination ($\tau = 0.17 \pm 0.004$, Bennett et al. 2003), which was based on TE alone.

Modelling cosmic reionization

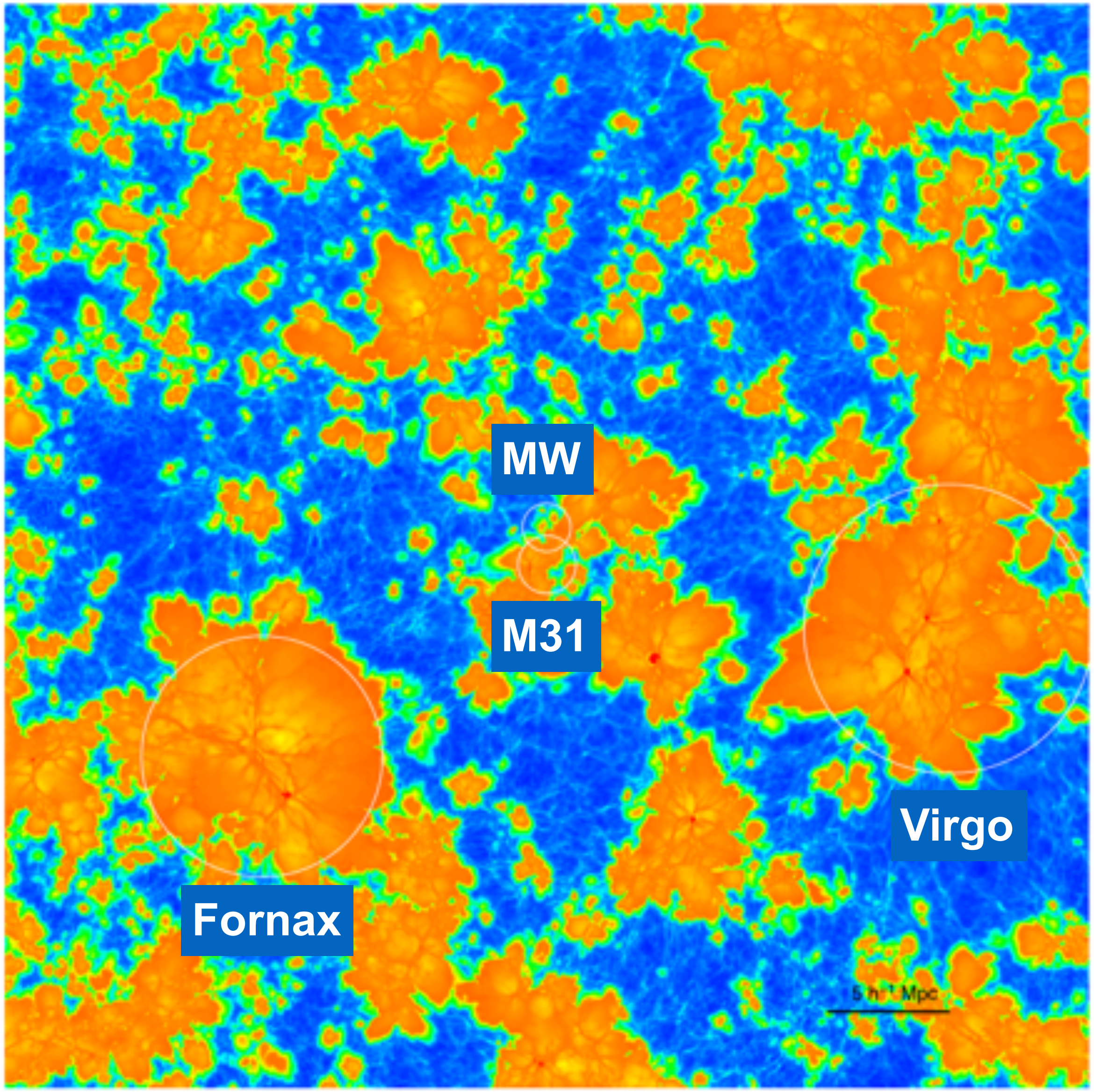
RAMSES-RT using M1 and GPU acceleration (CUDATON library).

Self-consistent model of the cosmic re-ionisation using dwarf galaxies as source of ionising radiation.

Initial conditions (WMAP5) were designed to reproduce our local universe (CLUES).

Used to derive interesting constraints on the SF history, the escape fraction…

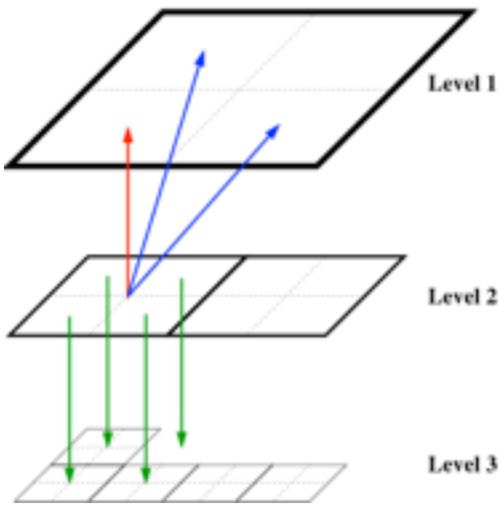
Ocvirk et al. (2015)



INCITE proposal 2013 (PI Shapiro/Teyssier)

RAMSES: parallel Adaptive Mesh Refinement

- Graded octree structure: the cartesian mesh is refined on a cell by cell basis
- Full connectivity: each oct have direct access to neighbouring parent cells and to children octs (memory overhead 2 integers per cell).
- Optimise the mesh adaptivity to complex geometry but CPU overhead can be as large as 50%.

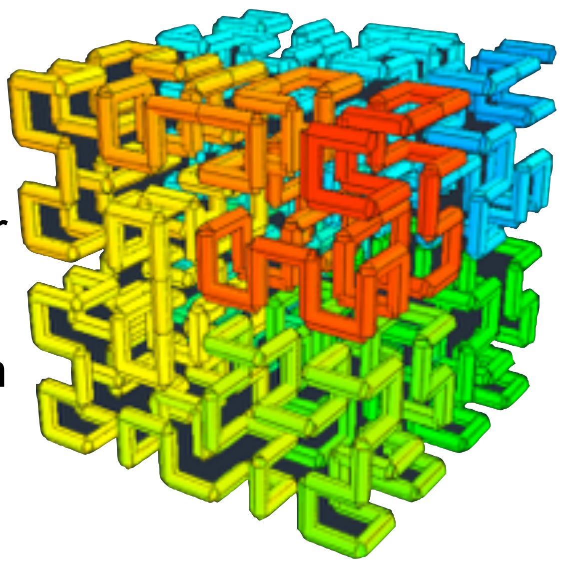


N body module: Particle-Mesh method on AMR grids. Poisson equation solved using a multigrid solver.

Hydro module: unsplit second order Godunov method (MUSCL) with various Riemann solvers and slope limiters. MHD solver with Constrained Transport.

Time integration: single time step or sub-cycling.

Other: radiative transfer, star formation, sink particles, stellar and AGN feedback



MPI-based parallel computing using time-dependent domain decomposition based on Peano-Hilbert cell ordering.

Download at **https://bitbucket.org/rteyssie/ramses**

A new radiation hydrodynamics solver in RAMSES

Radiative transfer equation: $$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \mathbf{n}\frac{\partial I_\nu}{\partial \mathbf{x}} = -\kappa_\nu I_\nu + \eta_\nu$$

Angular moment's equations:

$$\int_{4\pi} (\ldots)\,\mathrm{d}\Omega \longrightarrow \frac{\partial E_\nu}{\partial t} + \nabla\cdot\mathbf{F}_\nu = -\kappa_\nu c E_\nu + S_\nu$$

$$\int_{4\pi} (\ldots)\,\mathbf{n}\mathrm{d}\Omega \longrightarrow \frac{\partial \mathbf{F}_\nu}{\partial t} + c^2\nabla\cdot\mathbb{P}_\nu = -\kappa_\nu c\mathbf{F}_\nu$$

The geometry of the radiation field is encoded in the Eddington tensor. We approximate its angular distribution by a Lorentz-boosted dipole (Levermore 1984)

$$\mathbb{P}_\nu = E_\nu \mathbb{D}_\nu \quad \mathbb{D}_\nu = \frac{1-\chi_\nu}{2}\mathbb{I} + \frac{3\chi_\nu - 1}{2}\mathbf{n}_\nu \otimes \mathbf{n}_\nu,$$

$$\chi_\nu = \frac{3+4f_\nu^2}{5+2\sqrt{4-3f_\nu^2}} \quad \text{and} \quad \mathbf{f}_\nu = f_\nu \mathbf{n}_\nu = \frac{\mathbf{F}_\nu}{cE_\nu}$$

We obtain an hyperbolic system of conservation laws with source terms.
Numerical implementation similar to grid-based hydro solvers, using the Godunov method with a Lax-Friedrich Riemann solver.
Aubert & Teyssier (2008, 2010)
Rosdahl et al. (2013), Rosdahl & Teyssier (2014).

Implicit or explicit time integration

The Godunov method is based on the explicit time integration scheme.
The M1 approximation results in an effective "radiation fluid" with "sound waves" velocity close to the speed of light.
This gives a very restrictive Courant condition fro stability of the integration.
For one large hydro step, we usually need 100 to 1000 radiation sub-cycles.

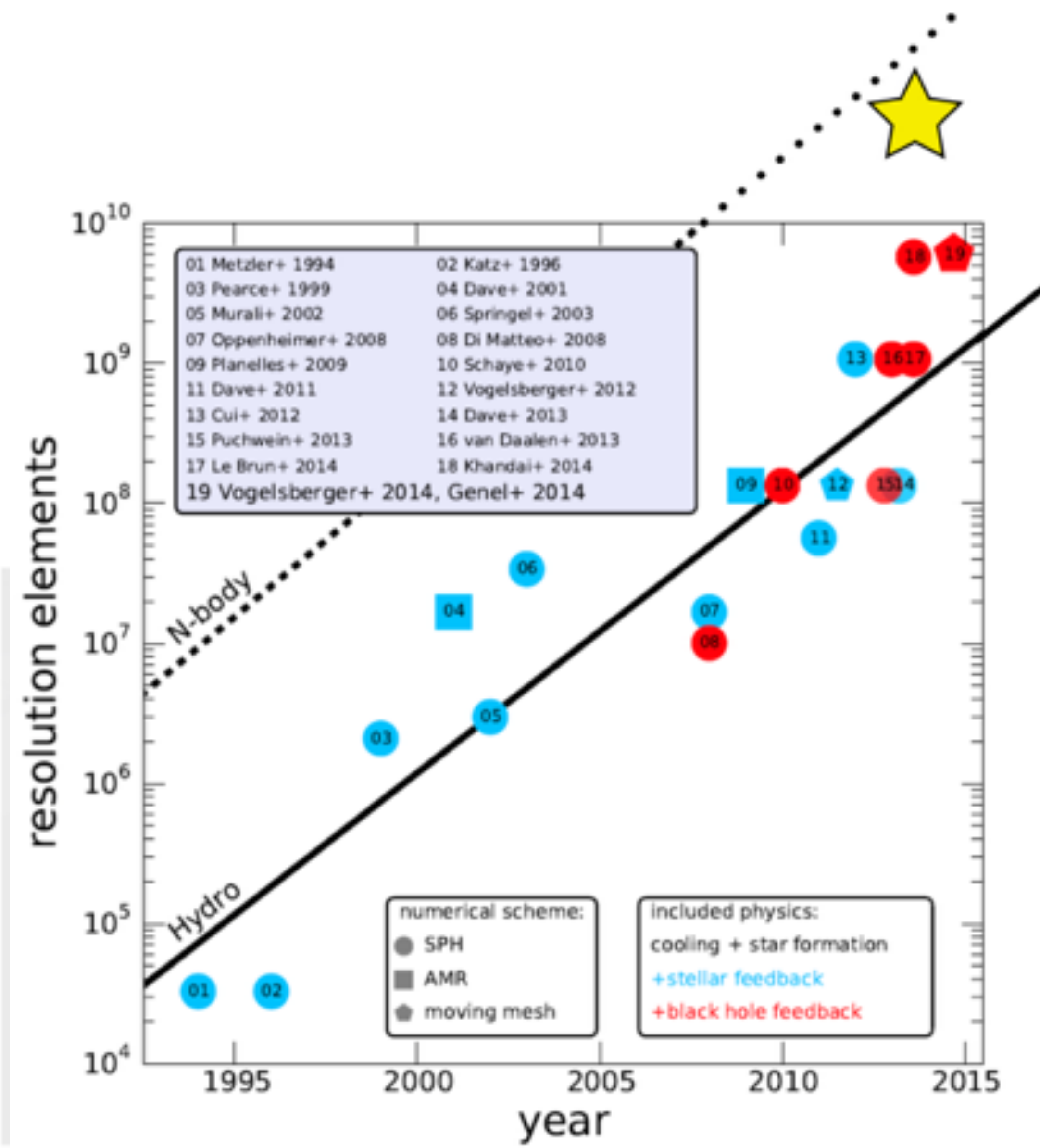
Solution 1: use the implicit time integration scheme. It is stable for large time steps but requires large sparse matrix solvers (CPU intensive, convergence and parallel computing issues) and can be inaccurate and slow in non-stationary cases.

Solution 2: reduce the speed of light *when valid ("slow light approximation")*.

Solution 3: use GPU acceleration to speed-up the explicit radiation solver, while using the correct value for speed of light, and compute the fluid evolution on the host.

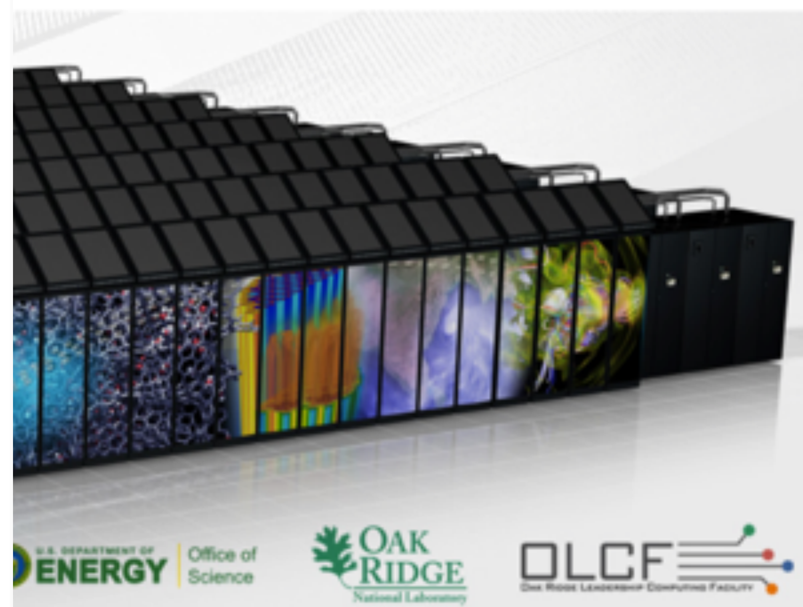
The third solution was implemented using the CUDA programming language on Nvidia graphics cards in the CUDATON library. Works only on Cartesian grids. (Aubert & Teyssier 2010).

TITAN at Oak Ridge National Laboratory

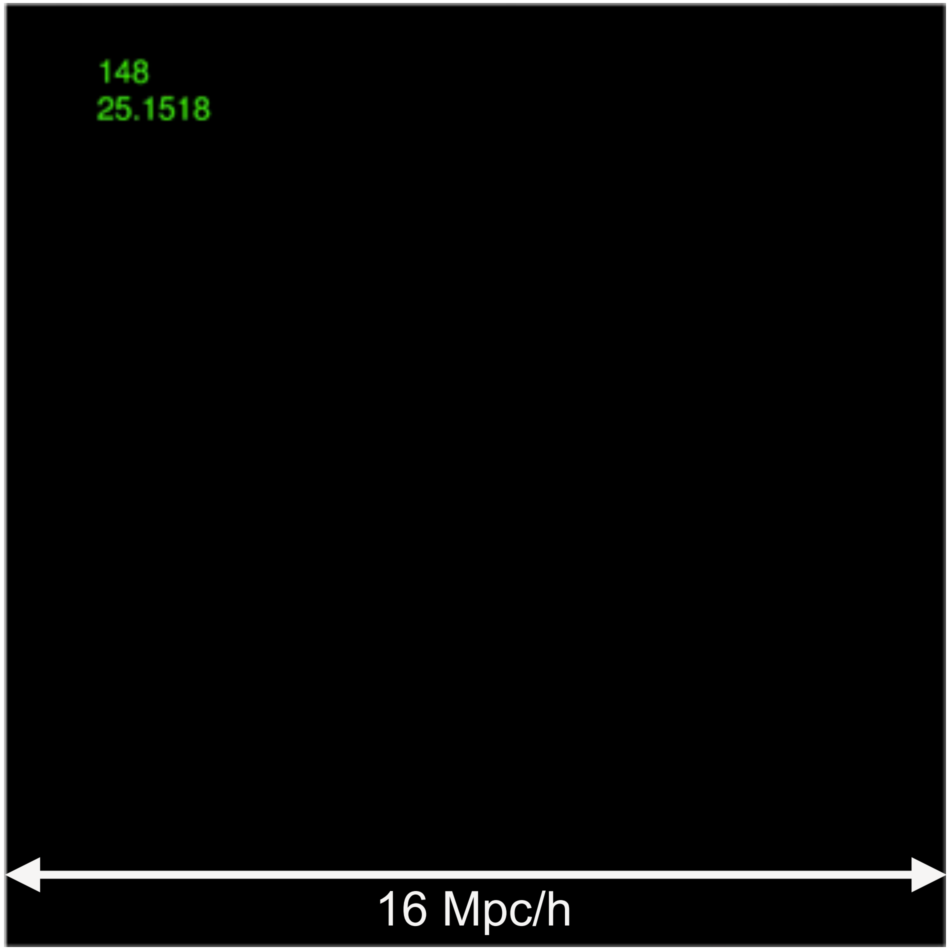


The CoDa simulation:

64 Mpc/h periodic box (no AMR)
4096^3 cells 15 kpc/h comoving
4096^3 dark matter particle
8192 Titan nodes
16 CPU and 1 GPU per node
11 days = 2 million node hours
2000 hydro time steps
1 million radiation time steps
140 snapshots, 2 PB of data



Cosmic reionization in a supercomputer



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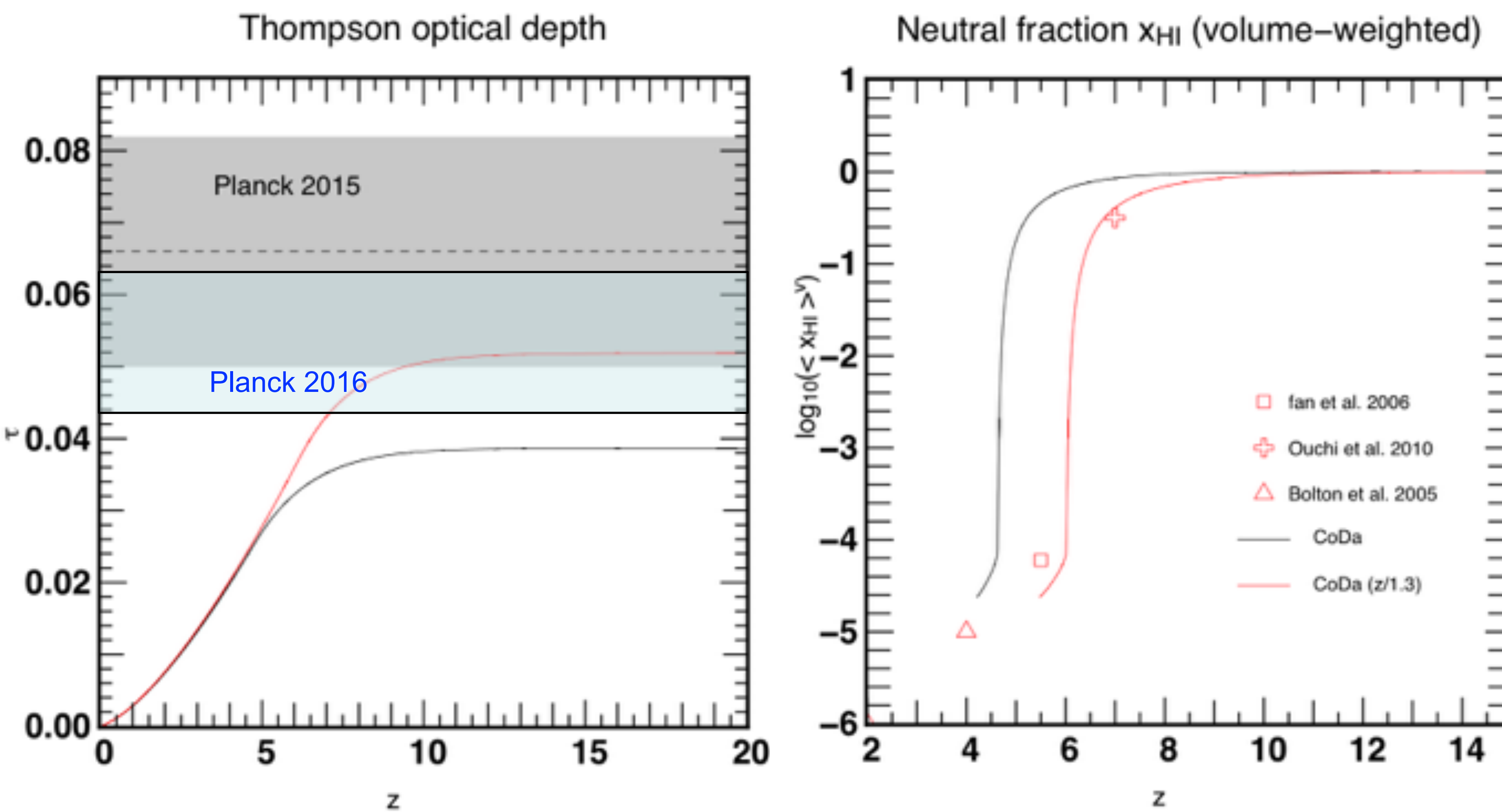
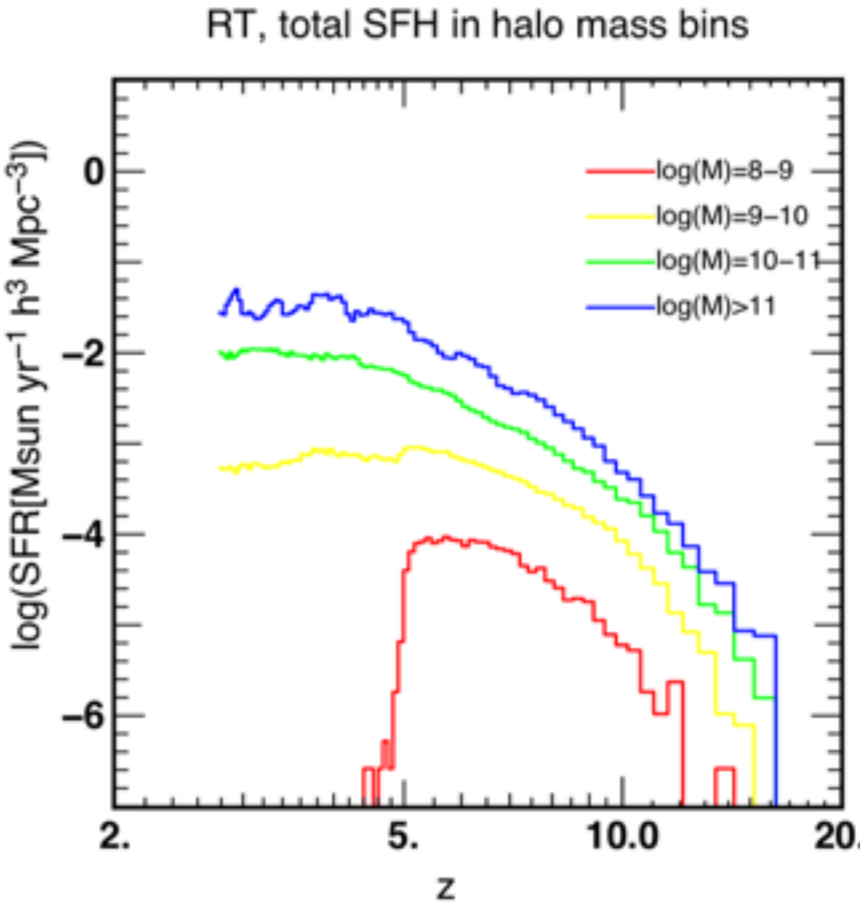


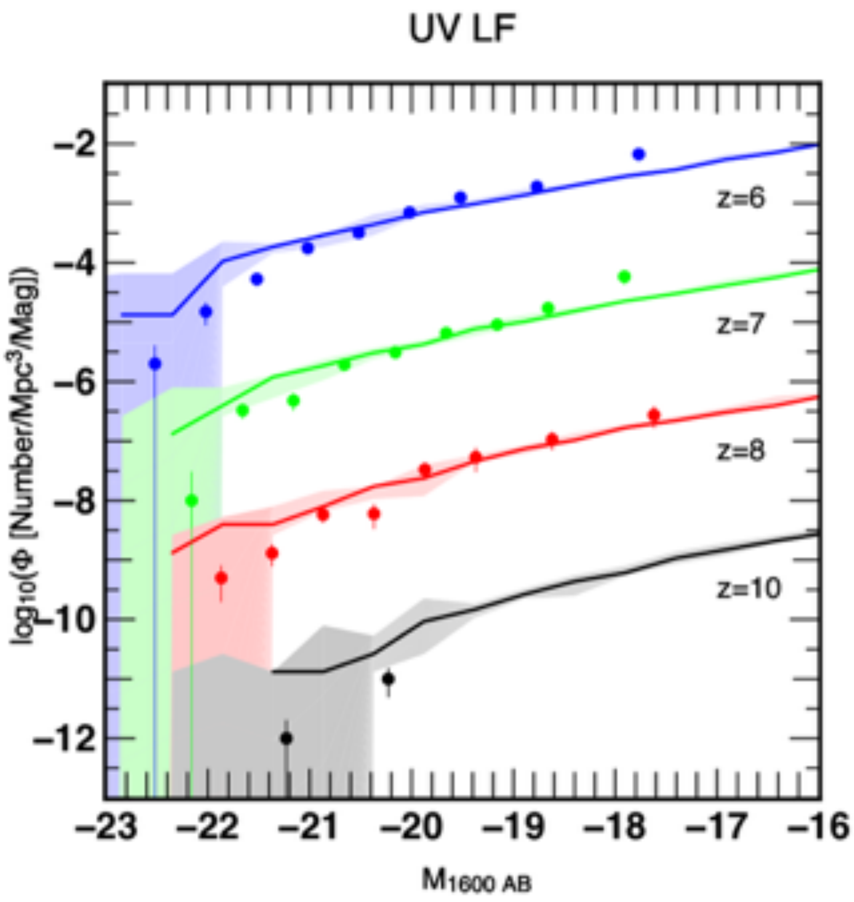
The adopted UV efficiency (escape fraction) proved slightly low.

Simple rescaling z=1.3*z matches observational constraints (Ocvirk et al. 2015).

Romain Teyssier

Radiation affects global galaxy properties



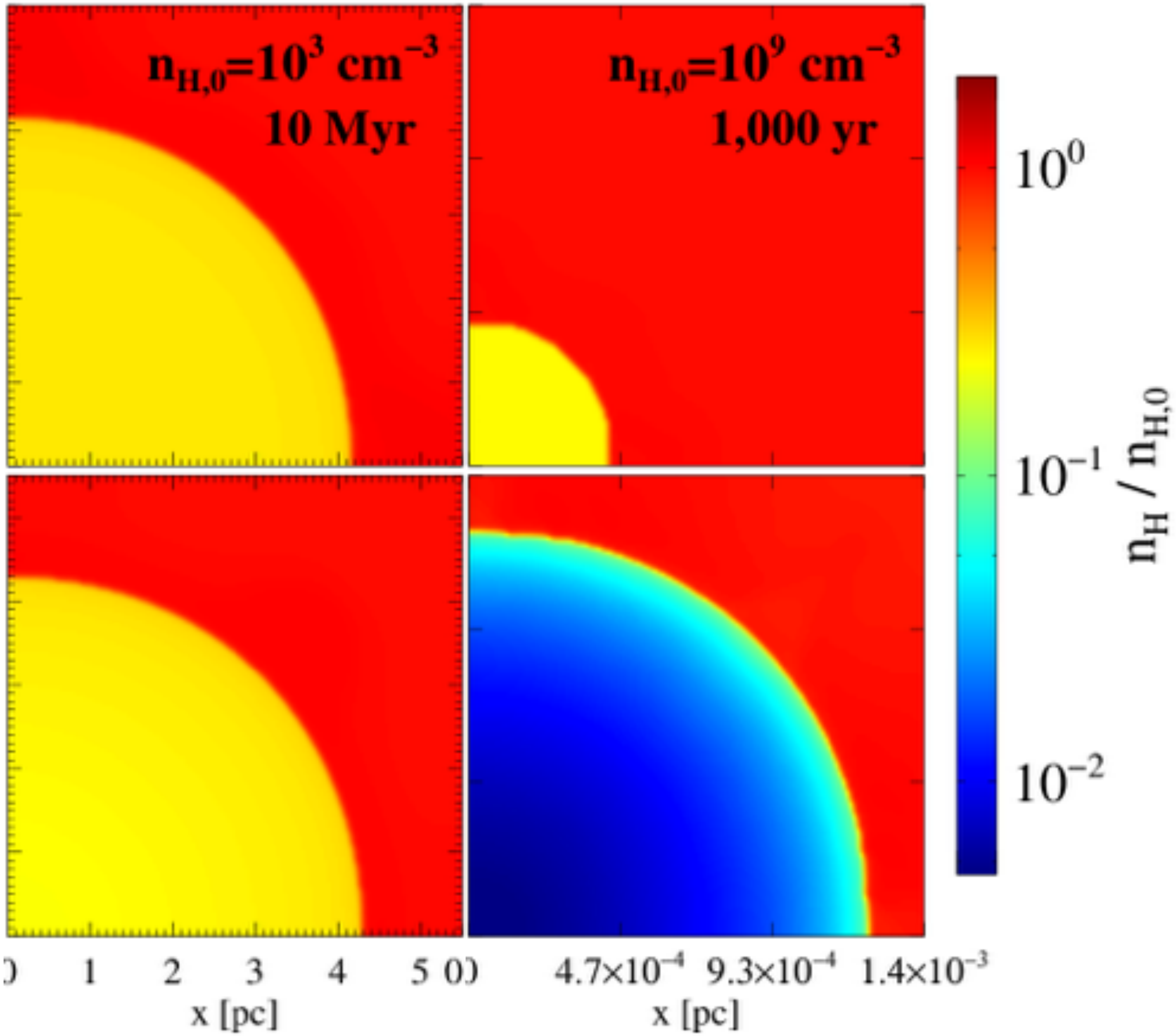


UV radiation pressure in ultra-compact HII regions

Rosdahl & Teyssier (2015)

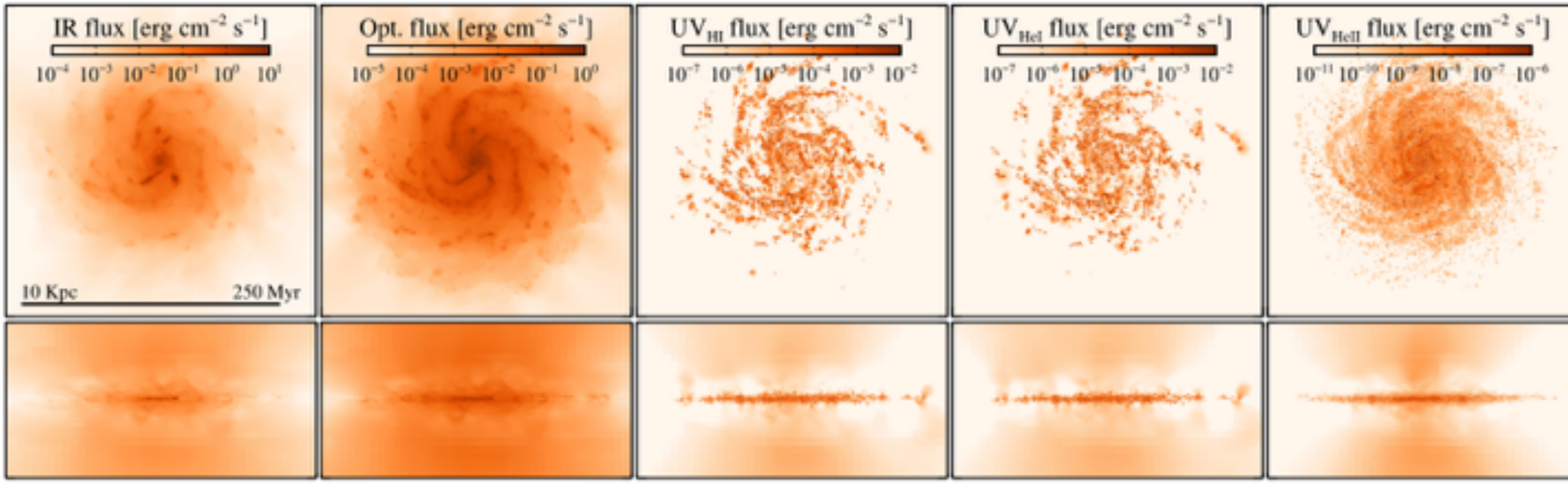
without radiation pressure

with radiation pressure



Galaxies that shine

Isolated galaxy with 5 different photons groups, photo-ionisation and dust absorption.



Rosdahl *et al.* (2015)

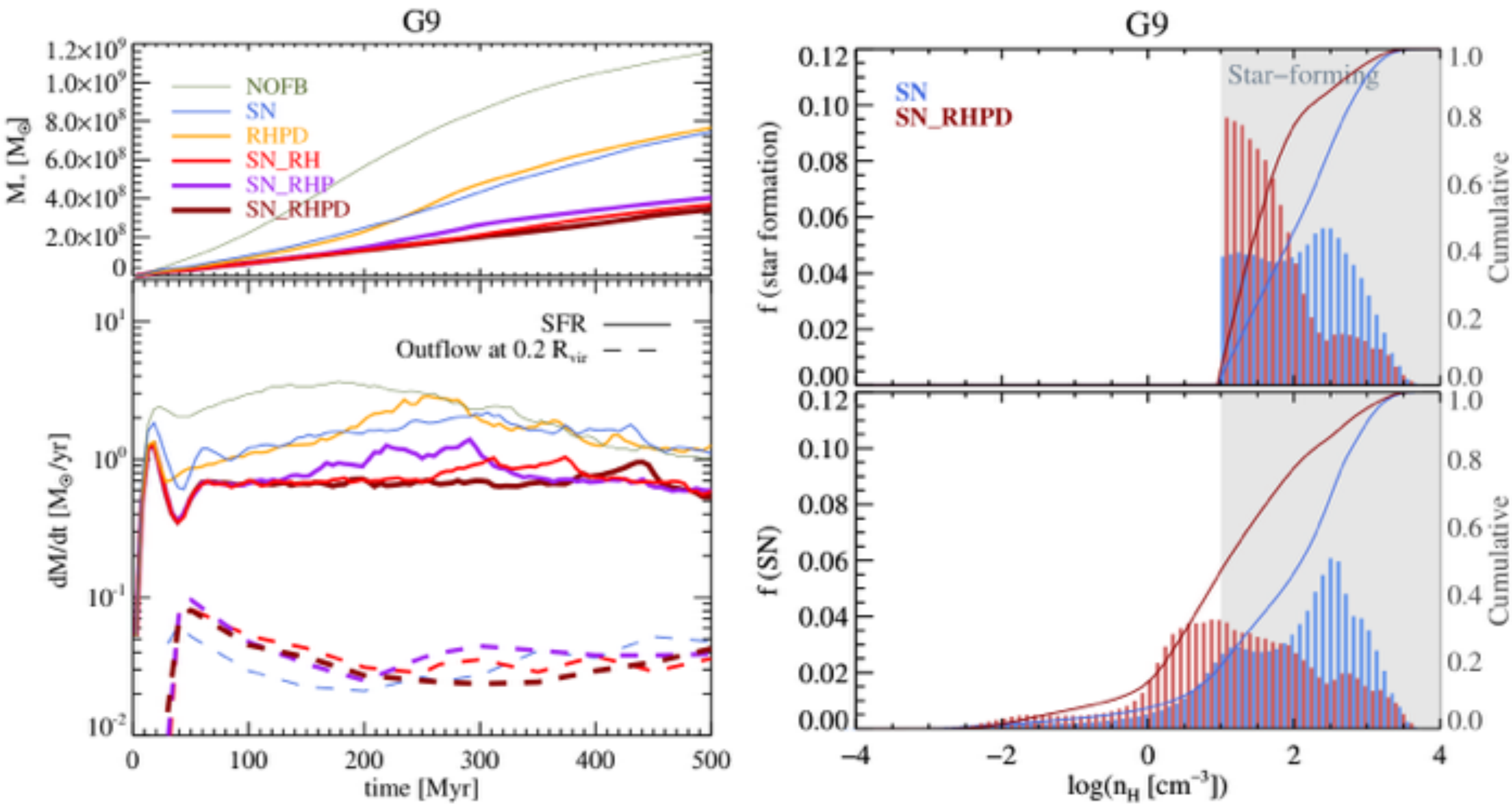
- 10^{11} solar masses halo
- $3x10^9$ solar masses baryonic disk
- 50% gas fraction.

- 10^6 stellar and DM particles
- 18 pc resolution
- 0.1 solar metallicity

Feedback processes:
- thermal SN energy injection (no trick)
- radiation from the B&C (2003) SEDs.
- HI and dust opacities

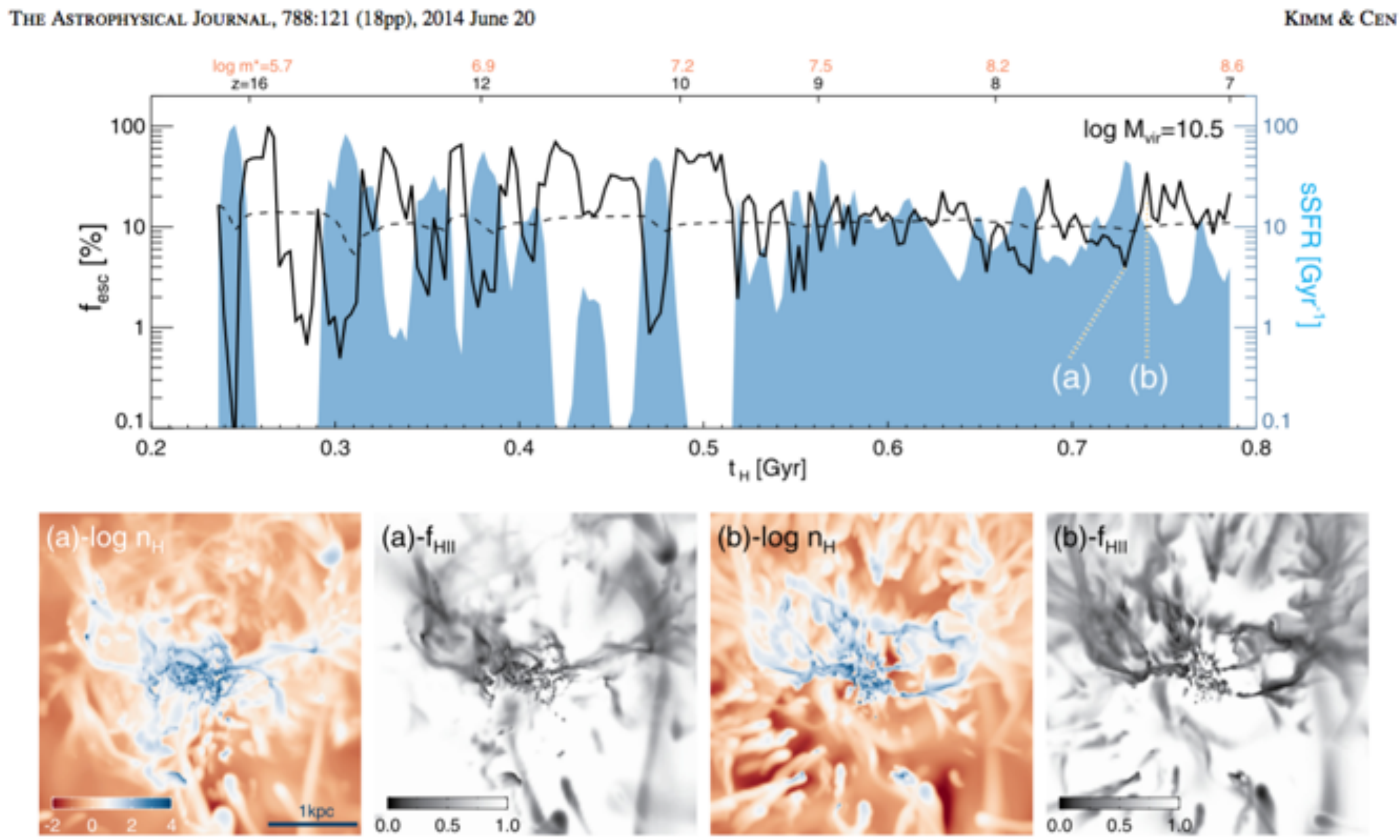
Radiative processes:
- photo-ionisation heating
- direct pressure from UV
- IR pressure from dust scattering

The interplay between radiation and supernovae



Rosdahl *et al.* (2015)

Computing the escape fraction



Conclusions

- cosmic reionization can be modelled self-consistently using radiation hydrodynamics for UV-ionising photons from early galaxies
  - key unknown: escape fraction from the complex ISM
  - numerical challenge: speed of light. GPU can be used to accelerate simple, robust explicit schemes
  - “witnessing our cosmic dawn”: the CoDa simulation on the Titan supercomputer

- simulations of radiation hydrodynamics within the ISM of star forming galaxies
  - radiation heating from UV photons, coupled to supernovae feedback
  - stellar feedback allows radiation to escape with 10% escape fraction.

Thank you !